U.S. Department of Transportation
**Federal Aviation Administration**

# Advisory Circular

**Subject:** FLUTTER SUBSTANTIATION OF TRANSPORT CATEGORY AIRPLANES
**Date:** 1/4/85
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**Change:**

1. PURPOSE. This advisory circular provides guidance material for acceptable means, but not the only means, of demonstrating compliance with the provisions of Part 25 of the Federal Aviation Regulations (FAR) dealing with the design requirements for transport category aircraft to preclude flutter and other aeroelastic phenomena. The precise detailing of analytical procedures and testing techniques is beyond the scope of this advisory circular. Some general considerations are set forth herein, with supportive discussion, to be considered in demonstrating compliance with § 25.629 and related regulations.

2. RELATED FAR SECTIONS.

§ 25.251 - Vibration and Buffeting
§ 25.343 - Design Fuel and Oil Loads
§ 25.571 - Damage-Tolerance and Fatigue Evaluation of Structure
§ 25.629 - Flutter, Deformation, and Fail-safe Criteria
§ 25.631 - Bird Strike Damage
§ 25.671 - Control Systems
§ 25.672 - Stability Augmentation and Automatic and Power-Operated Systems
§ 25.1309 - Equipment, Systems, and Installations
§ 25.1329 - Automatic Pilot System
§ 25.1419 - Ice Protection

3. BACKGROUND.

a. Flutter and other aeroelastic instability phenomena have had a significant influence on airplane development and the airworthiness criteria governing the design of civil aircraft. The initial requirement for consideration of flutter was minimal in the 1931 "Airworthiness Requirements of Air Commercial Regulations for Aircraft," Bulletin No. 7-A. The airplane flutter requirement specified that "no surface shall show any signs of flutter or appreciable vibration in any attitude or condition of flight." In 1934, Bulletin No. 7-A was revised in view of service experience and contained advice and good practice techniques for the early airplane designer regarding flutter prevention measures. All airplane designs were required to have interconnected elevators, statically balanced ailerons, irreversible or balanced tabs, and, in some cases, a ground vibration test was required to be conducted.

b. Regulations dealing specifically with flutter, deformation, and vibration on transport category airplanes were first introduced when Part 04 of the Civil Air Regulations (CAR) became effective in the mid-1940's. The criteria related the solution of the flutter problem to frequency ratios based on model tests conducted by the Army Air Corps. Also, based on the Army Air Corps developments, Part 04 imposed a design factor of 1.2 on equivalent airspeed to provide a stiffness margin for the airframe. In addition to this empirical approach and recognizing the advancing state-of-the-art, Part 04 referenced publications containing developing flutter theory.

c. The flutter requirement of Part 04 evolved into CAR 4b.308 where developing failsafe philosophy continued to change the scope of flutter substantiation. Among these developments was a revision to CAR 4b.320 in 1956 to require failsafe tabs and a revision to CAR 4b.308 in 1959 to require failsafe flutter damper installations. The flutter requirement was extensively revised in 1964 to require compliance with the single failure criteria for the entire airplane as well as special provisions for turboprop airplanes.

d. Service experience indicated that single failure criteria relating to flutter stability were not sufficiently objective and comprehensive to cover modern, complex, transport airplanes with highly redundant systems. Therefore, Part 25 of the FAR, which was recodified from Part 4b, was subsequently amended to require that unless combinations of failures are shown to be extremely improbable, they must be considered in design for freedom from flutter and divergence.

4. DISCUSSION OF REQUIREMENTS. The general requirement for demonstrating freedom from flutter, divergence, and control reversal is contained in § 25.629 of the FAR, which also sets forth specific requirements for investigation of these aeroelastic phenomena for airplane configurations and flight conditions. Additionally, there are other conditions defined by the FAR Sections listed in paragraph 2 above to be investigated for aeroelastic stability to insure safe flight.

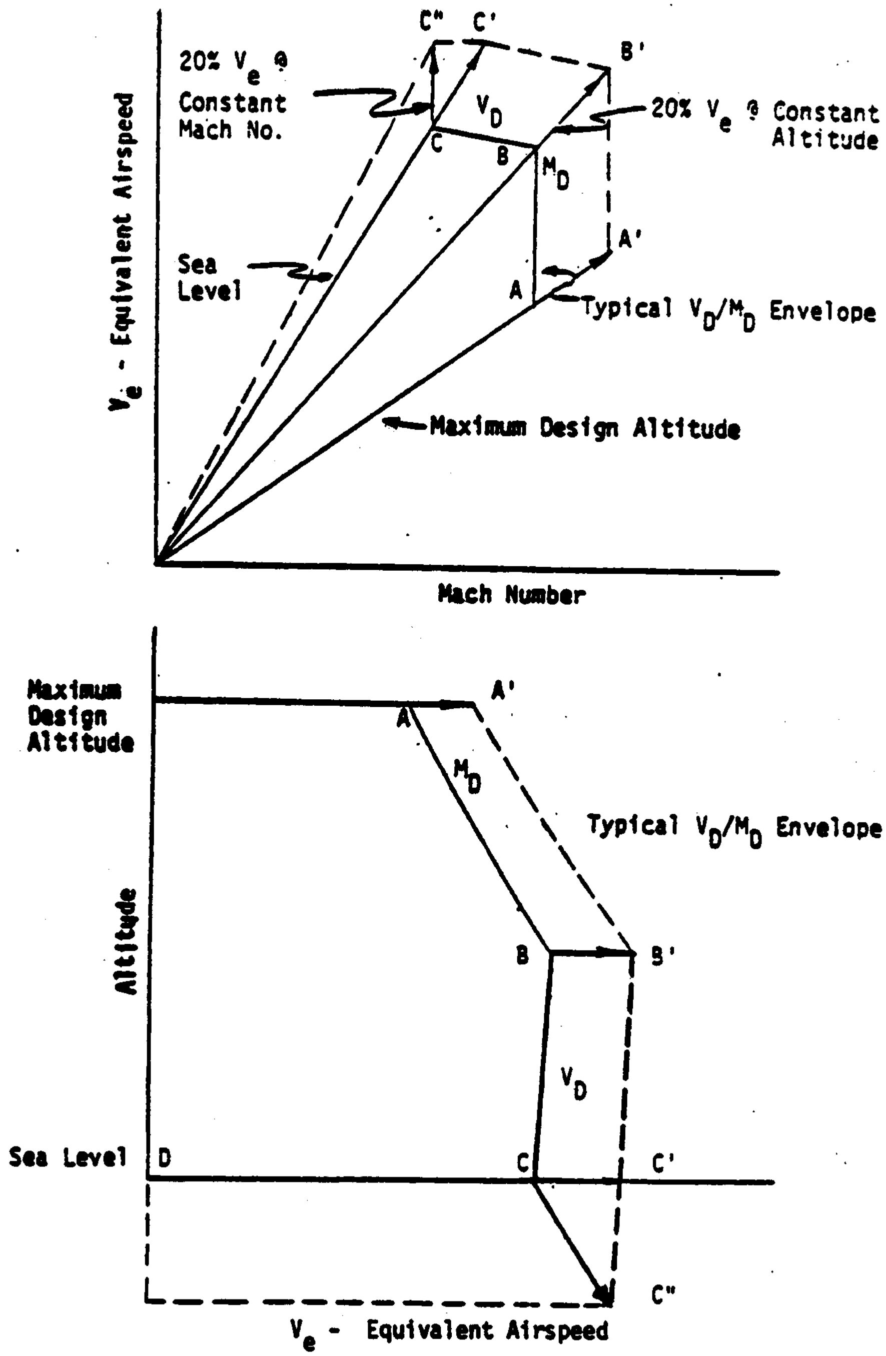
a. Flutter Clearance Envelope.

(1) Freedom from flutter, divergence, and control reversal is required to be shown for all combinations of airspeed and altitude encompassed by the design dive speed ($V_D$) and design Mach number ($M_D$) versus altitude envelope enlarged at all points by an increase of 20 percent in equivalent airspeed at both constant Mach number and constant altitude. Figure 1 represents a typical design envelope expanded to the required flutter clearance envelope. Note that some required Mach number and airspeed combinations correspond to altitudes below sea level.

(2) The flutter clearance envelope may be limited to a maximum Mach number of 1.0 when $M_D$ is less than 1.0 and there is no large and rapid reduction in damping as $M_D$ is approached.

(3) Some configurations and conditions that are required to be investigated by § 25.629 and other Part 25 regulations consist of failures, malfunctions, or adverse conditions. Flutter and divergence investigations of these conditions need be carried out only within the design airspeed versus altitude envelope up to $V_D/M_D$.

FIGURE 1. MINIMUM REQUIRED FLUTTER MARGIN



b. Configurations and Conditions. The following paragraphs provide a summary of the configurations and conditions to be investigated in demonstrating compliance with Part 25. Specific design configurations may warrant additional considerations not discussed in this advisory circular.

(1) Nominal Configurations and Conditions. Nominal configurations and conditions of the airplane are those that are likely to exist in normal operation. Freedom from flutter, divergence, and control reversal should be shown throughout the expanded clearance envelope described in paragraph a above for:

(i) The range of fuel and payload combinations, including zero fuel in the wing, for which certification is requested.

(ii) Configurations with critical ice mass accumulations on unprotected surfaces for airplanes approved for operation in icing conditions.

(iii) All normal combinations of autopilot, yaw damper, or other automatic flight control systems.

(2) Failures, Malfunctions, and Adverse Conditions. The following conditions should be investigated for flutter and divergence within the design envelope to $V_D/M_D$.

(i) The condition of all engines failed for the design range of fuel and payload combinations, including zero fuel in the wing.

(ii) Any critical fuel loading conditions which may result from mismanagement of fuel.

(iii) For airplanes not approved for operation in icing conditions, the maximum likely ice accumulations that may result from an inadvertent encounter.

(iv) The maximum damage likely to occur from impact with a bird in the empennage area as described in § 25.631.

(v) The discrete source damage conditions of § 25.571(e).

(vi) The failure of each principal structural element for which failsafe strength is demonstrated under § 25.571(b).

(vii) Any single failure, or malfunction, or combinations thereof, in the flight control system under § 25.671, § 25.672, or § 25.1309, and any single failure in any flutter damper system.

(viii) Any single failure of the stability augmentation system, or any other automatic or power operated system.

(ix) The failure of any single element of the structure supporting any engine; independently mounted propeller shaft; or large, externally mounted aerodynamic body.

(x) Any single failure of the engine structure that would reduce the yaw or pitch rigidity of a large engine fan or propeller rotational axis.

(xi) The absence of propeller aerodynamic or gyroscopic forces resulting from feathering of any single propeller or the most adverse combination of two or more propellers for airplanes with four or more engines.

(xii) The effect of a single feathered propeller coupled with the failure of a single element of structure supporting any engine or independently mounted propeller shaft.

(xiii) Any single propeller rotating at the highest likely overspeed.

(xiv) Any other combinations of failures not shown to be extremely improbable.

c. <u>Detail Design Requirements</u>.

(1) Main surfaces, such as wings and stabilizers, should be designed to meet the flutter and divergence criteria for nominal conditions and should be investigated for meeting failsafe criteria by considering stiffness changes due to discrete damage or by reasonable parametric variations of design values.

(2) Control surfaces, including tabs, should be investigated for nominal conditions and for failure modes that include single structural failures (such as actuator disconnects, hinge failures, or in the case of aerodynamic balance panels, failed seals), single and dual hydraulic system failures and any other combination of failures not shown to be extremely improbable. Where other structural components contribute to the flutter stability of the system, failures of those components should be considered for possible adverse effects.

(3) Consideration of free play may be incorporated as a variation in stiffness to assure adequate limits are established for wear of components such as control surface actuators, hinge bearings, and engine mounts in order to maintain flutter clearance margins.

(4) If concentrated balance weights are used on control surfaces, their effectiveness and strength, including support structure, should be substantiated on a rational basis.

(5) The automatic flight control system should not couple with the airframe to produce flutter. When analyses indicate possible coupling, tests should be performed to determine the dynamic characteristics of actuating systems such as servo boost, fully powered servo control, closed-loop airplane flight control systems, stability augmentation systems, and other related powered-control systems. Guidance and criteria applicable to active flutter suppression systems are provided by AC 25.672-1, Active Flight Controls.

(6) Oscillatory failures of the automatic flight control systems should be assessed. Of primary concern for oscillatory failures are the resultant dynamic loads. The saturated frequency response of the control systems and surfaces may be evaluated by tests or by conservative analyses. Dynamic loads may be analytically determined using the saturated frequency response of the control surface as a definition of the control surface deflection relative to the frequency of oscillation. Guidance and criteria applicable to oscillatory failures of the automatic flight control system are contained in AC 25.1329-1A, Automatic Pilot Systems Approval. Investigation of forced structural vibration resulting from failures, malfunctions, or adverse conditions in the automatic flight control systems may be limited to airspeeds up to $V_C$.

5. COMPLIANCE. Demonstration of compliance with flutter requirements for an aircraft configuration may be shown by analyses, tests, or some combination thereof. In most instances, flutter analyses are required to establish the sensitivity of the aircraft to significant parameters and to determine flutter margins for normal operations, as well as for possible failure conditions. Wind tunnel flutter model tests may be used to demonstrate flutter stability to the expanded design speed boundary for the nominal aircraft and to show clearance to $V_D$ for structural failure conditions. Ground testing may be used to collect stiffness or modal data for the aircraft or components. Flight testing may be used to demonstrate compliance of the aircraft design throughout the design dive speed envelope.

a. Analytical Investigations. Flutter analyses may be used to investigate the flutter stability of the aircraft throughout its design flight envelope and as expanded by the required speed margins. Analyses are employed to evaluate flutter sensitive parameters such as stiffness and mass distributions, control surface balance requirements, fuel management schedules, engine/store locations, and control system characteristics. The sensitivity of most critical parameters may be determined analytically by varying the parameters from nominal. These investigations are an effective way to account for the operating conditions and possible failure modes which may have an effect on flutter margins, and to account for uncertainties in the values of parameters and expected variations due to in-service wear or failure conditions.

(1) Analytical Modeling. The following sections discuss acceptable, but not the only, methods and forms of modeling aircraft configurations and/or components for purposes of flutter analysis. The types of investigations generally encountered in the course of aircraft flutter substantiation are also discussed. The basic elements to be modeled in flutter analyses are the elastic, inertial, and aerodynamic characteristics of the system. The degree of complexity required in the modeling and the degree to which other characteristics need to be included in the modeling depend upon the system complexity.

(i) Analytic Structural Modeling. Most forms of structural modeling can be classified into two main categories: (1) beam modeling, and (2) finite element modeling. Regardless of the approach taken for structural modeling, a minimum acceptable level of sophistication, consistent with configuration complexity, is necessary to satisfactorily represent the critical modes of deformation of the primary structure and control surfaces. The model should reflect the support structure for the attachment of control surface actuators, flutter dampers, and any other elements for which stiffness is important in flutter prevention. Wing-pylon mounted engines are often significant in flutter and warrant particular attention in the modeling of the pylon, and pylon-engine and pylon-wing interfaces. The model should include the effects of cutouts, doors, and other structural features which may tend to affect the resulting structural effectiveness. Reduced stiffness should be reflected in modeling of aircraft structural components which may exhibit some change in stiffness under design flight conditions.

(ii) Analytic Aerodynamic Modeling.

(A) Aerodynamic modeling for flutter requires the use of unsteady, two-dimensional strip or three-dimensional panel theory methods for incompressible or compressible flow. The choice of the appropriate technique depends on the complexity of the dynamic structural motion of the surfaces under investigation and the flight speed envelope of the aircraft.

(B) Surface aerodynamic data are commonly adjusted by weighting factors in the flutter solutions. The weighting factors for steady flow (k=0) are usually obtained by comparing aerodynamic wind tunnel test results with theoretical data. Special attention must be given to control surface aerodynamics because viscous and other effects may require more extensive adjustments to theoretical coefficients.

(2) Types of Analyses.

(i) Oscillatory (flutter) and non-oscillatory (divergence and control reversal) aeroelastic instabilities should be analyzed to show compliance with § 25.629 of the FAR.

(ii) The flutter analysis methods most extensively used involve the modal analysis with unsteady aerodynamic forces derived from various two- and three-dimensional theories. These methods are generally for linear systems. Analyses involving control system characteristics should include equations describing system control laws in addition to the equations describing the structural modes.

(iii) Airplane lifting surface divergence analyses should include all appropriate rigid body mode degrees-of-freedom since divergence may occur for a structural mode or the short period mode.

(iv) Loss of control effectiveness (control reversal) due to the effects of elastic deformations should be investigated. Analyses should include the inertial, elastic, and aerodynamic forces resulting from a control surface deflection.

(3) Structural Damping Requirements.

(i) Flutter analyses results are usually presented graphically in the form of frequency versus velocity (V-f, Figure 2) and structural damping versus velocity (V-g, Figures 3 and 4) curves for each root of the flutter solution.

(ii) Figure 3 details one common method for showing analytic compliance with the requirement for a proper margin of damping. It is based on the assumption that the structural damping available in the structure is 0.03 and is the same for all modes as depicted by the V-g curves shown in Figure 3. No significant mode, such as curves (2) or (4), should cross the g = 0 line below $V_D$ or the g = 0.03 line below $1.2V_D$. An exception to this rule is a mode exhibiting damping characteristics similar to curve (1) in Figure 3, which is not critical for flutter. A divergence mode, as illustrated by curve (3) where the frequency approaches zero, should have a divergence velocity not less than $1.2V_D$.

(iii) Figure 4 shows another common method of presenting the flutter analysis results and defining the structural damping requirements. The modal damping for each mode is entered into the analysis prior to the flutter solution, resulting in modes offset from the g = 0 line at zero airspeed and, in some cases, flutter solutions different from those obtained with no structural damping. The similarity in the curves of Figures 3 and 4 are only for simplifying this example. The minimum acceptable damping line in Figure 4 is equal to 0.03 or the modal damping available at zero airspeed for the particular mode of interest, whichever is less, but in no case less than 0.02. No significant mode should cross this line below $V_D$ or the g = 0 line below $1.2V_D$.

FIGURE 2. FREQUENCY VERSUS VELOCITY

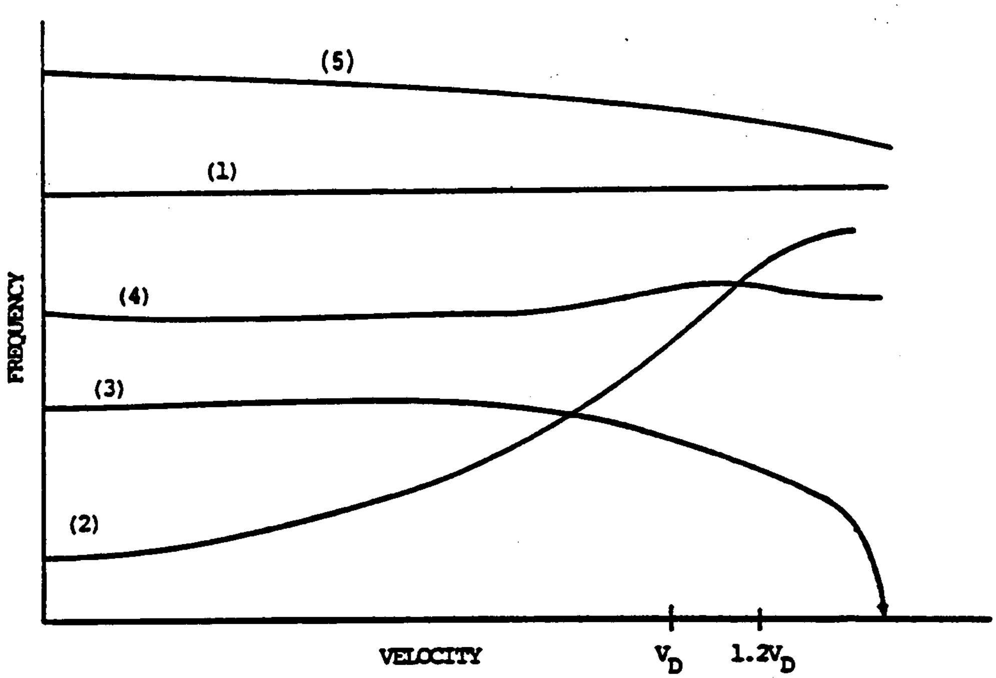


FIGURE 3. DAMPING VERSUS VELOCITY - Method 1

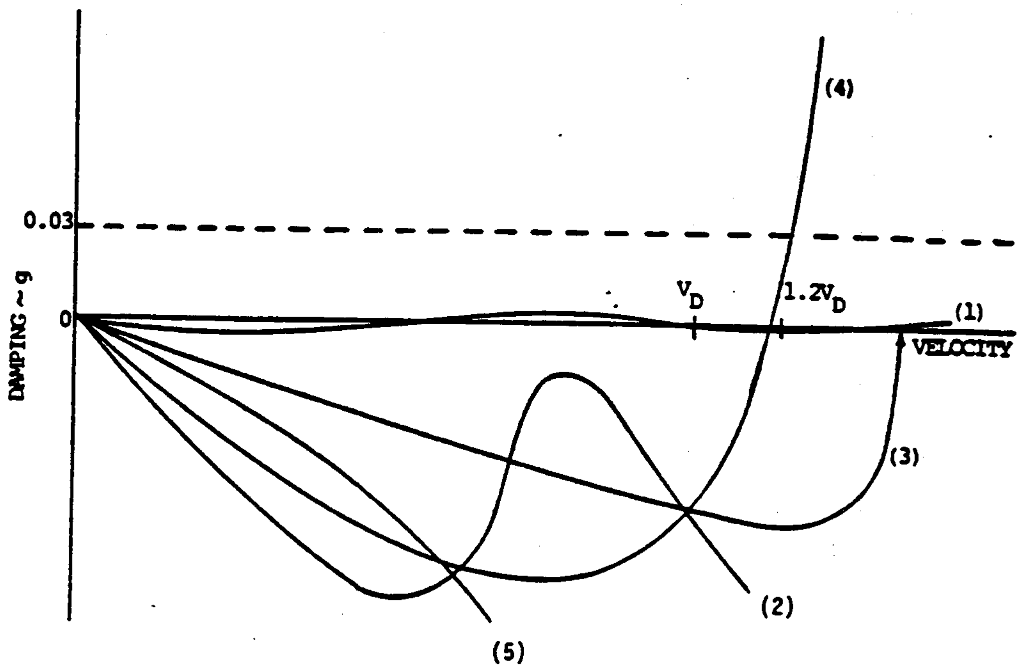
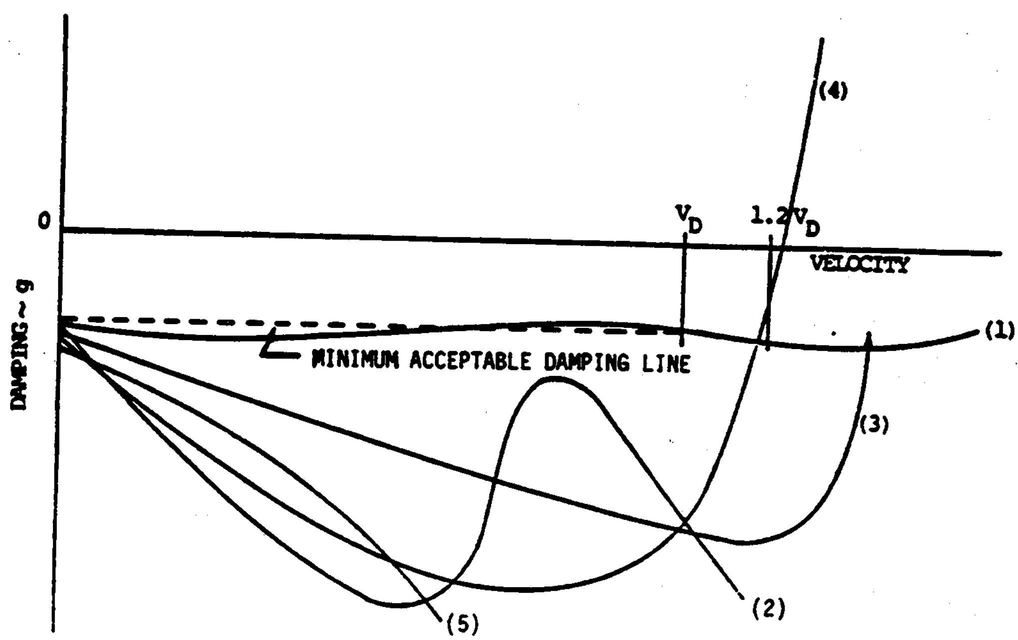



FIGURE 4. DAMPING VERSUS VELOCITY - Method 2



(4) Analysis Considerations. Airframe flutter analyses may be used to verify the design with respect to the design structural stiffness, mass, fuel (including in-flight fuel management), automatic flight control system characteristics, and altitude and Mach number variations within the design flight envelope. The complete airplane should be considered as composed of lifting surfaces and bodies, including all primary control surfaces which can interact with the lifting surfaces to affect flutter stability. Control surface flutter can occur in any speed regime and has historically been the most common form of flutter. Lifting surface flutter is more likely to occur at high dynamic pressure and at high subsonic and transonic Mach numbers. Analyses are necessary to establish the mass balance and/or stiffness and redundancy requirements for the control surfaces and supporting structure and to determine the basic surface flutter trends. The analyses may be used to determine the sensitivity of the nominal aircraft design to aerodynamic, mass, and stiffness variations. Sources of stiffness variation may include the effects of skin buckling at limit load factor, air entrapment in hydraulic actuators, expected levels of in-service free play, and control system components which may include elements with nonlinear stiffness. Mass variations include the effects of fuel density and distribution, control surface repairs and painting, and water and ice accumulation.

(i) Control Surfaces. Control surface flutter analyses should include control surface rotation, tab rotation (if applicable), significant modes of the airplane, control surface torsional degree-of-freedom, and control surface bending (if applicable). Analyses of airplanes with tabs should include tab rotation that is both independent and related to the parent control surface. Control surface rotation frequencies should be varied about nominal values as established by analysis and/or test data. The control surfaces should be analyzed as completely free in rotation unless it can be shown that this condition is extremely improbable. The aerodynamic coefficients of the control surface and tab used in the flutter analysis should be adjusted to match experimental values at zero frequency. Once the analysis has been conducted with the nominal, experimentally adjusted values of hinge moment coefficients, the analysis should be conducted with parametric variations of these coefficients and other parameters subject to variability. If flutter margins are found to be sensitive to these parameters, then additional verification in the form of model or flight tests may be required.

(ii) Mass Balance.

(A) The magnitude and spanwise location of control surface balance weights may be evaluated by analysis and/or wind tunnel flutter model tests. If the control surface torsional degrees of freedom are not included in the analysis, then adequate separation must be maintained between the frequency of the control surface first torsion mode and the flutter mode.

(B) Control surface unbalance tolerances should be specified to provide for repair and painting. The accumulation of water, ice, and/or dirt in or near the trailing edge of a control surface should be avoided. Free play between the balance weight, the support arm, and the control surface must not be allowed. Control surface mass properties (weight and static unbalance) should be confirmed by measurement before ground vibration testing.

(C) The balance weights and their supporting structure should be substantiated for the extreme load factors expected throughout the design flight envelope. In the absence of a rational investigation, the following limit load factors may be used for balance weights.

100g normal to the plane of the surface.
30g parallel to the hinge line.
30g in the plane of the surface perpendicular to the hinge line.

(iii) Flutter Dampers. Control surface flutter dampers may be used to prevent flutter in the event of failure of some element of the control surface actuation system or to prevent control surface buzz. Flutter analyses and/or flutter model wind tunnel tests may be used to verify adequate damping. Damper support structure flexibility should be included in the determination of adequacy of damping at the flutter frequencies. Single damper failures should be considered. When considering redundant damper configurations, all combinations of single damper failures should be examined to ensure the remaining dampers provide flutter safety. Combinations of multiple damper failures should be examined when not shown to be extremely improbable. The combined free play of the damper and supporting elements between the control surface and fixed surfaces should be considered. Provisions for in-service checks of damper integrity should be considered.

(iv) Intersecting Lifting Surfaces. Intersecting lifting surface flutter characteristics are more difficult to predict accurately than the characteristics of planar surfaces such as wings. This is due to difficulties both in correctly predicting vibration modal characteristics and in assessing those aerodynamic effects which are of second order importance on planar surfaces, but are significant for intersecting surfaces. Proper representation of modal deflections and unsteady aerodynamic coupling terms between surfaces is essential in assessing the flutter characteristics. The in-plane forces and motions of one or the other of the intersecting surfaces may have a strong effect on flutter speeds; therefore, the analysis should include the effects of steady flight forces and elastic deformations on the in-plane effects.

(v) Ice Accumulation.

(A) Aircraft certified for operation in icing conditions should be able to meet the flutter clearance requirements with the mass distributions derived from the maximum likely ice accumulations for any unprotected surfaces. The required freedom from flutter must be shown throughout the airspeed-altitude envelope as prescribed in paragraph 4a as modified by the envelope requirements of § 25.1419, Appendix C. The analyses need not consider the aerodynamic effects of ice shapes.

(B) For aircraft that are not approved for operation in icing conditions, the inadvertent encounter with icing conditions is considered to be an "adverse condition." Under this failsafe criterion, freedom from flutter with mass distributions derived from the maximum likely ice accumulations should be shown by analysis at airspeeds up to $V_D/M_D$ as modified by the envelope requirements of § 25.1419, Appendix C. The ice accumulation determination can take into account the ability to detect the ice and the time required to leave the icing conditions.

(vi) Whirl Flutter.

(A) The evaluation of the flutter and divergence integrity should include investigations of any significant elastic, inertial, and aerodynamic forces, including those associated with rotations and displacements in the plane of any turbofan or propeller, including propeller or fan blade aerodynamics, powerplant flexibilities, powerplant mounting characteristics, and gyroscopic coupling.

(B) Failure conditions are usually significant for whirl instabilities. Engine mount, engine gear box support, or shaft failures which result in a node line shift for propeller hub pitching or yawing motion are especially significant.

(C) A wind tunnel test with a component flutter model, representing the engine/propeller system and its support system along with correlative vibration and flutter analyses of the flutter model, may be used to demonstrate adequate stability of the nominal design and failed conditions.

(vii) Gain and Phase Variations in Flight Control Systems. Flutter analyses of the basic configuration should include simulation of the flight control system to determine if adverse coupling exists between the sensing elements of the flight control system and the structural modes. The effect of flight control system failures on the airplane flutter characteristics should be investigated. Failures which significantly affect the system gain and/or phase and are not shown to be extremely improbable should be analyzed. Guidance for requirements for flutter suppression and wing load alleviation systems may be found in AC 25.672-1, Active Flight Controls.

b. Testing. The flutter certification test program may consist of ground tests, flutter model tests, and flight flutter tests. Ground tests may be used for assessment of component stiffness and for determining the vibration modal characteristics of aircraft components and the complete airframe. Flutter model testing is used to establish flutter trends and validate flutter boundaries in areas where analytic unsteady aerodynamic calculations require confirmation. Full scale flight flutter testing provides final verification of flutter integrity. The results of any of these tests may be used to provide flutter substantiation data, to verify and improve analytic modeling procedures and data, and to identify potential or previously undefined problem areas.

(1) Stiffness Tests. Stiffness tests of structural components are desirable to confirm predicted characteristics and are necessary where stiffness calculations cannot accurately predict these characteristics. Components should be mounted so that the mounting characteristics are well defined or readily measurable.

(2) Control System Component Tests. Actuators for primary flight control surfaces and flutter dampers should be tested with their supporting structure. These tests are to determine the actuator/support structure

stiffness for nominal design and failure conditions considered in the failsafe analysis. Flutter damper tests should be conducted to verify the desired complex compliance of damper and support structure to assure satisfactory installed damper effectiveness at the potential flutter frequencies. The results of these tests can be used to determine a suitable, inservice maintenance schedule and replacement life of the damper. In addition, free play measurements of the installed damper should be performed to verify that the free play is within limits.

(3) Ground Vibration Tests.

(i) Ground vibration tests (GVT) or modal response tests are normally conducted on the complete airplane in its conforming and flightworthy condition. A GVT may be used to check the mathematical structural model. However, upon structurally or inertially modifying a previously certified design, a GVT may not be necessary if the changes do not affect flutter or a GVT validated model of the basic airplane is used and the effects of the changes can be properly assessed analytically. The use of measured modal data alone in subsequent flutter analyses, instead of analytical modal data modified to match test data, may be acceptable provided the accuracy and completeness of the measured modal data is established.

(ii) The airplane is best supported such that the suspended airplane rigid body modes are effectively uncoupled from the elastic modes of the airplane. Alternatively, a suspension method may be used that results in rigid body/flexible mode coupling, provided that the suspension can be analytically decoupled from the airplane structure in the vibration analysis. The former suspension criterion is preferred for all ground vibration tests and is necessary in the absence of vibration analysis.

(iii) The excitation method needs to have sufficient force output and frequency range to adequately excite all significant resonant modes. The effective mass and stiffness of the exciter and attachment hardware should not distort modal response. More than one exciter or exciter location may be necessary to insure that all significant modes have been identified. Multiple exciter input may be necessary on structures with significant internal damping to avoid low response levels and phase shifts at points on the structure distant from the point of excitation. Excitation may be by sinusoidal, random, psuedo-random, transient, or other short duration, nonstationary means.

(iv) The minimum modal response measurement should consist of acceleration (or velocity) measurements and relative phasing at a sufficient number of points on the airplane structure to accurately describe the response or mode shapes of all significant structural modes. In addition, the structural damping of each mode should be determined.

(4) Flutter Model Tests.

(i) Flutter models may be used to substantiate the flutter margin in areas where flutter analysis results are not always reliable; e.g., control surface flutter, T-tails, and flutter where compressibility effects may be significant.

(ii) Low speed wind tunnel tests of a flutter model can be used to assess the effect on flutter of such parameters as stiffness, fuel weight, payload, control surface mass balance and rotation stiffness, external store shape, mass, and attachment stiffness, structural interconnection stiffnesses, etc. This type of model can be used to establish trends and the relative effectiveness of parametric variations.

(iii) High speed models can provide additional support that a particular design configuration is flutter-free throughout the expanded design envelope, and that specific failsafe conditions are flutter-free for speeds up to $V_D/M_D$.

(iv) For both low and high speed tests, the model mounting method is important. For a complete model, all significant rigid body degrees of freedom should be permitted with sufficiently low frequencies to assure proper coupling of structural modes. Component flutter models should be mounted such that aerodynamic interactions are not significantly altered and attachment stiffnesses are representative of the full scale component or can be accounted for by analysis.

(5) Flight Flutter Tests.

(i) Full scale flight flutter testing of an airplane configuration to $V_{DF}/M_{DF}$ is a necessary part of the flutter substantiation. An exception may be made when aerodynamic, mass, or stiffness changes to a certified airplane are minor, and analysis or ground tests show a negligible effect on flutter or vibration characteristics. If a failure, malfunction, or adverse condition is simulated during a flight test, the maximum speed investigated need not exceed $V_{FC}/M_{FC}$ if it is shown, by correlation of the flight test data and with other test data or analyses, that flutter will not occur at any speed up to $V_D/M_D$.

(ii) Flight configurations and test conditions should be selected which have the lowest flutter speed/damping combination based on analyses and model test results. These configurations should then be tested and should include automatic flight control system operational checks. Analytic evaluations may be used to determine the flight test configurations and conditions.

(iii) Substantiation of an airplane by flight flutter testing requires excitation sufficient to excite the modes shown by analysis to be the most likely to couple for flutter. Control surface motions are often adequate sources of excitation. Alternative methods include internal moving mass or external aerodynamic exciters or flight turbulence. The effect of the excitation system itself on the airplane flutter characteristics should be determined prior to flight testing.

(iv) Measurement of the response at selected locations on the structure should be made in order to determine the damping in the critical modes at each test airspeed. It is desirable to monitor the response amplitude and damping change as $V_{DF}/M_{DF}$ is approached. As a minimum, a record should be made of the response to the airplane excitation at $V_{DF}/M_{DF}$.

## APPENDIX 1. RELATED READING MATERIAL

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